Diurnal Evolution of the Hourly Diffuse Solar Radiation Incident on Tilted Surfaces in Southeast of Brazil

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Abstract

Evaluation has been made on the monthly and annual average diurnal evolution of the hourly diffuse radiation as well as its radiometric fractions on surfaces inclined at 12.85, 22.85 and 32.85° to face North, in climate conditions of Botucatu, São Paulo, Brazil (22.85° S and 48.43° W). Measurements were made between 04/1998 to 08/2001 for 22.85°; 09/2001 to 02/2003 for 12.85° and 01/2004 to 12/2007 for 32.85°, with concomitant measures in the horizontal. For all surfaces the diffuse radiation was obtained from different method. Assessment has been performed as well on the radiometric fractions obtained from the ratio of diffuse radiation and global radiation (K_{DH} and $K_{D\beta}$) and between radiation and diffuse radiation at the top of the atmosphere (K'_{DH} and $K'_{D\beta}$) for the horizontal and tilted surfaces in hourly partition. The diffuse radiation levels were dependent on variations in precipitation and cloudiness. There was an increase in the differences between the diffuse radiation and the radiometric fractions with the increment of the angle, and in horizontally, which affected higher levels of diffuse radiation in spring and summer. The values of K_{DH} and $K_{D\beta}$ present in an inverse behavior were compared to diffuse radiation and theydecreased in the southern passage due to the increase of the direct component in the total of incident radiation.

Keywords

Solar Radiation; Solar Energy; Atmospheric Transmissivity; Radiometric Fractions

Introduction

Robust technological development has been witnessed in Brazil in the areas of renewable energy (photovoltaic and photothermal conversion, wind, biomass and biodiesel), agriculture (with increase of efficiency based on physical and physiological properties of crops and/or animals) and civil construction (constructive materials, micrometeorological aspects, among others). All these advancements lead to an increasing demand for knowledge of seasonal variations of the levels of solar radiation, concerning the spectral components and the atmospheric attenuation (Martins & Pereira, 2008; Martins et al., 2011; Pereira et al., 2012).

The temporal variation of the amount of solar radiation incident at any location on the earth's surface basically depends on astronomical, geographical and climatic factors (concentrations of water vapour, aerosols and clouds in atmosphere). According to Liou (2002), the seasonal variations in the levels of each component of solar radiation relies on the interaction with the atmosphere. Some atmospheric constituents are relatively constant in concentration (permanent gases), while others are highly variable in time and space (such as CO_2, methane, water vapour and aerosols), thus allowing that the current composition and concentration vary with geographical location, altitude and season of year.

Among local characteristics, the variations of altitude, inclination (slope), orientation (azimuth) and shading may affect the solar energy levels (mainly the geometry of incidence of direct solar fluxes). The incident global radiation in horizontal planes comprises the direct and diffuse component, whereas in tilted surfaces, there is also the contribution of reflected energy fluxes (Iqbal, 1983; Burlon et al., 1991). In general, the direct and reflected components are obtained from specific geometric approaches based on projections and measurements in horizontal surface (Notton et al., 2006; Gueymard et al., 2009; El-Sebaii et al., 2010).

For the diffuse component, there are no geometric

relationships that enable simplified applications based only on measure in horizontal. This is justified because this radiation presents particular characteristics resulting from atmospheric isotropy and anisotropy (scattering) and must be assessed by considering the sub-components circunsolar, brightness and isotropic diffuse radiation (Chwieduk, 2009; Posadillo & Luque, 2009).

The instruments for measurements of solar radiation are basically of two types: i) the pyranometers measure the global radiation, diffuse (when positioned under systems of interception of direct radiation) and reflected radiation (when positioned to the reflective surface); ii) pyrheliometers, that measure only direct radiation incidence. Due to the costs involved in the acquisition and instruments maintenance of measurements for spectral and/or atmospheric interactions in brazilian conditions, the routine monitoring of solar radiation is linked to universities and research institutes (Codato et al., 2008; Martins & Pereira, 2008; Escobedo et al., 2009; Borges et al., 2010; Martins et al., 2011; Piacentini et al., 2011; Viana et al., 2011; Furlan et al., 2012; Pereira et al., 2012).

Most meteorological stations in Brazil operate measurements only on the global radiation in horizontal surface. Due to the demand for data from direct and diffuse components the search for technologies proved that allow obtaining measurements with low cost is justified. The major limitations for applications in tilted surfaces are the supplies databases of diffuse component with various time series (diurnal, monthly and yearly) and spatial scales, when available, the routine measures require the application of corrections resulting from the diffuse radiation blocking shading system (rings and discs). The methodologies of correction apply geometric parameters (constructive measures of equipment), astronomical and climatic conditions to enable the evaluation of atmospheric attenuation by isotropy and anisotropy (Oliveira et al., 2002; Dal Pai & Escobedo, 2006; Pandey & Katiyar, 2009; Padovan & Del Col, 2012).

The radiometric station of Botucatu (at 22°53′S of latitude and 48°26′W of longitude) belonging to the School of Agronomic Sciences, State University of São Paulo, has been continuously and simultaneously monitoring the global radiation, direct normal incident and diffuse radiation by the ring of shading method since April 1998. This study is utilized to evaluate the monthly average and annual average from the hourly diffuse radiation and from coefficients of diffuse atmospheric transmissivity (radiometric fractions), incident in horizontal and tilted surfaces at 12.85°, 22.85° and 32.85° (corresponding to latitude-10°, latitude and latitude+10 °, respectively).

Materials and Methods

Site and Measurements

The data of global, direct and diffuse radiation used in this work has been measured at the radiometric station, at 22°53′S of latitude and 48°26′W of longitude, located in the rural area of Botucatu city, in the country side of State of São Paulo, Brazil (Fig. 1a). Botucatu, a city with 119.3 thousand habitants, is located in the countryside of Brazil, at 786 m above the mean sea level, and approximately 221 km far away from the Atlantic Ocean (Fig. 1b). For the Köppen climatic classification, the climate is Cwa type, characterized with humid temperate, mild cold and dry winter (June–August) and warm and wet summer (December–February). The averaged air temperature varies from a minimum of 16.5°C in the winter to a maximum of 23.9 °C in the summer. The minimum precipitation occurs in August and the maximum in January (Dal Pai & Escobedo, 2006; Codato et al., 2008; Escobedo et al., 2009).

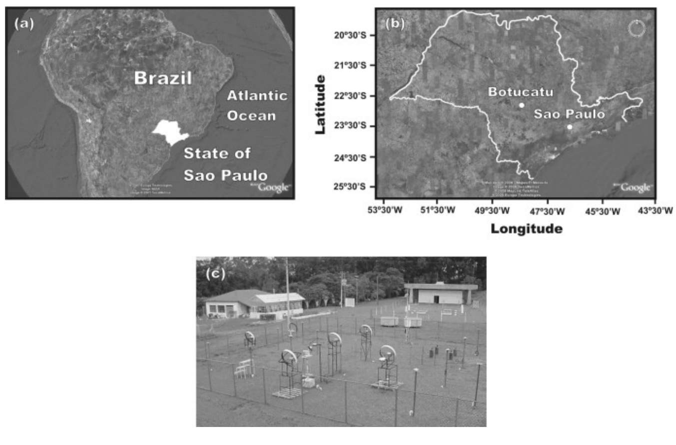

FIG. 1 GEOGRAPHIC POSITION OF THE (A) STATE OF SÃO PAULO; (B) BOTUCATU AND (C) VIEW OF THE NW QUADRANT OF THE RADIOMETRIC STATION IN BOTUCATU, STATE OF SÃO PAULO, BRAZIL [13].

Evaluations conducted on three inclinations, with slopes of 12.85° (latitude - 10°), 22.85° (latitude) and 32.85° (latitude + 10°) occurred in different periods: between 09/2001 and 02/2003 to 12.85°; 04/1998 and 08/2001 to 22.85°; 03/2004 and 12/2007 to 32.85°. Independent period measurements were concomitant with measurement on horizontal surface. Analysis was performed on consistency of databases and outliers (derived from reading errors or malfunction of the

sensors and system data acquisition) were removed from the databases.

Measurements were considered instant values when obtained from average in five minutes (300 readings). The acquisition system Microlloger CR23Xwas employed to operate a frequency of 1 Hz and a memory module SM192 interface with SC532 microcomputer run by software PC 208 W, both of Campbell Scientific, Inc. and the instant global horizontal irradiation (IGH) was measured by an Eppley pyranometer-PSP with calibration factor of 7.45 μV W-1 m-2 and linearity of ± 0.5% (0-2800 W m-2). For instant global tilted radiation (IGβ) used CM3 pyranometer from Kipp & Zonenholding response sensitivity of ± 10-35 μV W-1 m-2, a response time of 18s, the temperature response of ± 1.0% for the range of -40°C to 80°C and deviations for the cosine effect of ± 2% (0 < z <80°).

The direct radiation instantaneous incidence (IBN) was obtained from a pireliometer Eppley NIP-coupled to a solar tracker ST3 Eppley with calibration factor of 7.59 μV W-1 m-2 and linearity of ± 0.5% (0-1400 W m-2).

Data Processing

The hourly diffuse radiations on horizontal [$H^h_{D\beta}$] and tilted surfaces [$H^h_{D\beta}$] were obtained from difference method (eqs. 01 and 02). Assessments were made on the seasonality by the acquisition of the average annual and monthly schedules of energy.

$$H^h_{DH} = H^h_{GH} - H^h_{BH} \tag{01}$$

$$H^h_{D\beta} = H^h_{G\beta} - H^h_{B\beta} - H^h_{R\beta} \tag{02}$$

Therefore, the hourly global radiation was obtained from integration of the instantaneous values; so did the projection of hourly direct radiation on the horizontal surface [$H^h_{B\beta}$] resulting from the product between the measure and the incidence zenital angle for horizontal surface (eq. 03).

$$H^h_{BH} = H^h_{BN} \cos Z_H \tag{03}$$

According to Iqbal (1983) the projection of radiation direct to hourly inclined planes [$H^h_{B\beta}$] is given by the geometrical relationship between the extraterrestrial radiation to an inclined surface and a horizontal surface or the ratio of the cosine of the zenith angles inclined (Zβ) and horizontal (ZH) (eq. 04).

$$R_B = H^h_{0\beta} / H^h_{0H} \quad \text{or} \quad R_B = \cos Z_\beta / \cos Z_H \tag{04}$$

where: H^h_{0H} and $H^h_{0\beta}$ are extraterrestrial radiation to horizontal and the inclined surfaces respectively, obtained from eqs. 05 and 06 described by Iqbal (1983).

$$H^h_{0H} = H_{SC}\, E_0 \,[(\sin\delta \sin\phi) + (\cos\delta \cos\phi \sin \omega_s)] \tag{05}$$

$$H^h_{0\beta} = H_{SC}\, E_0 \,[\sin\delta \sin(\phi\pm\beta) + \cos\delta \cos(\phi\pm\beta) \sin \omega'_s] \tag{06}$$

where: H_{SC} is the solar constant (4921 KJ m^{-2} h^{-1}); ϕ is location latitude; δ is hourly solar declination solar (eq. 07) dependent on season (DJ – Julian day); E_0 is the factor correction of the eccentricity of Earth's orbit (eq. 06a); ω_s and ω'_s are the hourly angle by horizontal and tilted surfaces, respectively (eqs. 07 and 08).

$$\delta = 23.45 \sin [(360/365)*(DJ+284)] \tag{05}$$

$$E_0 = 1.00011 + 0.034221\cos\Gamma + 0.00128\sin\Gamma + 0.000719\cos2\Gamma + 0.000077\sin2\Gamma \tag{06a}$$

$$\Gamma = 2\pi [(DJ - 1)/365] \tag{06b}$$

$$\omega_s = \cos^{-1} (- \tan\delta \tan\phi) \tag{07}$$

$$\omega'_s = \min \{\cos_{-1} (- \tan\delta \tan\phi) ; \cos^{-1} [-\tan\delta \tan(\phi\pm\beta)] \tag{08}$$

The hourly reflected component [$H^h_{R\beta}$] incident on tilted surfaces may have isotropic and anisotropic behavior, however, the anisotropy should be applied only for days with clear skies and clean. Due to the variability of sky cover conditions in Botucatu, only the isotropic behavior was ken into consideration, which was given by eq. 09 (Iqbal, 1983; Kamali et al., 2006; Gueymard, 2009; Teramoto & Escobedo, 2012), which in turn was dependent on surface albedo (α) regarded as 0.23 for reference crop.

$$H^h_{R\beta} = 0,5\, H^h_{GH}\, \alpha\, (1 - \cos\beta) \tag{09}$$

The hourly diffuse fractions and the coefficients of atmospheric transmissivity of diffuse radiation (eqs. 10 at 13) were evaluated for the horizontal and three inclined surfaces.

$$K^h_{DH} = H^h_{DH} / H^h_{GH} \tag{10}$$

$$K^h_{D\beta} = H^h_{D\beta} / H^h_{G\beta} \tag{11}$$

$$K'^h_{DH} = H^h_{DH} / H^h_{0H} \tag{12}$$

$$K'^h_{D\beta} = H^h_{D\beta} / H^h_{0\beta} \tag{13}$$

Results And Discussion

Due to the existence of few graphical information of the behavior of solar radiation on inclined surfaces under Brazilian conditions, Fig. 2 shows a series of diurnal extraterrestrial radiation throughout the year. It was observed that the hourly levels of $H^h_{0\beta}$ are superior to H^h_{0H} between March and November, with the increase of the differences of the tilt angle. In the equinoctial months (March and September), regardless of the angle of inclination of the surface, the values of the hourly extraterrestrial radiation are close but with lower values for the horizontal due to higher zenith angle.

At local noon (the culmination of the plan of local meridian), the minimum values of extraterrestrial radiation are 3.37 (June), 3.99 (June), 4.38 (June) and 4.36 MJ m^{-2} h^{-1} (January) to horizontal, 12.85° and 22.85° and 32.85° surfaces, respectively. The maximum values (the same hour) are 5.08 (January), 5.03 (February), 4.96 (March) and 4.64 MJ m^{-2} h^{-1} (June) for the same surfaces. Therefore, the annual average values (solar noon) are 4.39±0.66, 4.65±0.39, 4.72±0.18 and 4.64±0.20 MJ m^{-2} h^{-1} to horizontal, 12.85°, 22.85° and 32.85°.

The diurnal annual average evolution of diffuse radiation (Fig. 3, considering the concomitant measurement in the same period between the horizontal and each inclination) shows that in the hours near the sunrise and sunsets, the $H^h_{D\beta}$ and H^h_{DH} values are low and similarwith quantitative differences occurring in culmination of the local plane of meridian.

According to Teramoto and Escobedo (2012) in the hours near the sunrise and sunset, the atmospheric optics mass, zenith angles and distance are increased the transversing along the atmosphere for radiative fluxes, which make the occurrence of greater attenuation of direct radiation possible through interaction with atmospheric constituents by the processes of scattering, absorption and reflection, and consequently of the anisotropy (Liou, 2002).

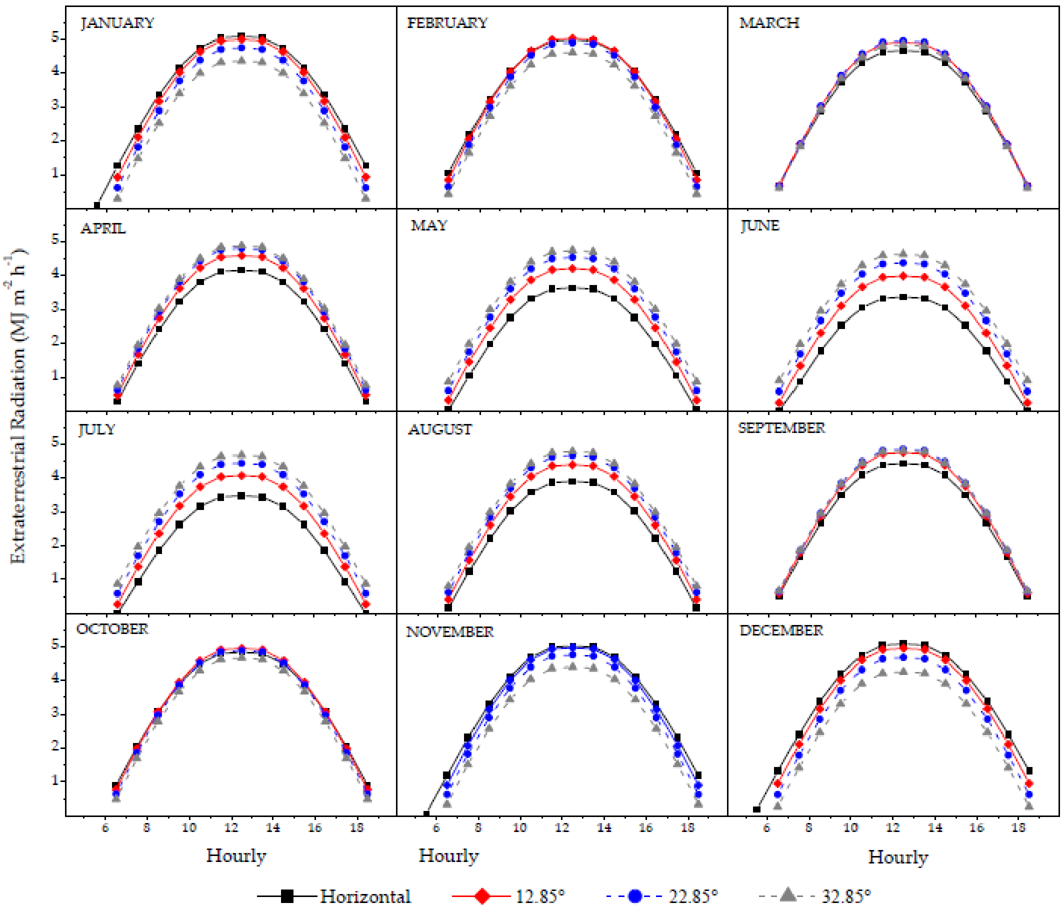

FIG. 2 MONTHLY AVERAGE OF THE DIURNAL EVOLUTION OF EXTRATERRESTRIAL RADIATION FOR HORIZONTAL SURFACE [H^h_{0H}] AND SURFACES WITH DIFFERENT ANGLES OF INCLINATION TO THE NORTH [$H^h_{0\beta}$].

The increase in the angle of inclination decreases the mean hourly diffuse energy at local noon around 1.04±0.76, 0.96±0.65 and 0.80±0.69 for 12.85°, 22.85° and 32.85° and also 1.12±0.76, 1.03±0.63 and 1.00±0.10 MJ m^{-2} h^{-1} to horizontal surface for the same periods of inclined planes respectively (Fig. 3).

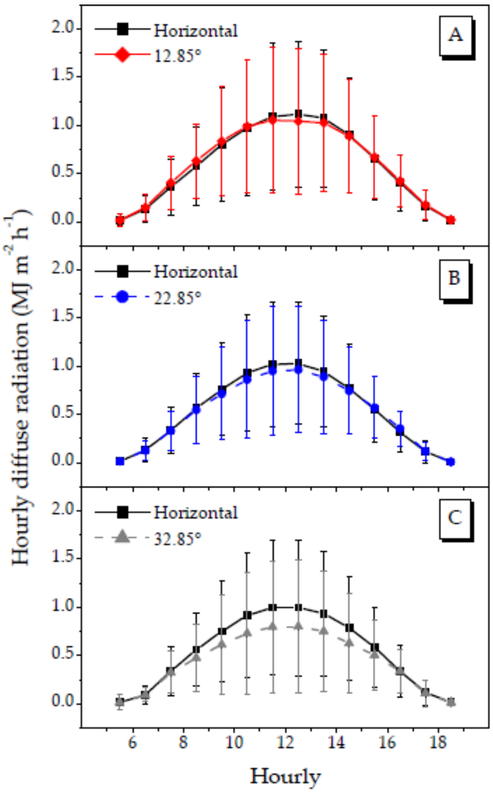

FIG. 3 DIURNAL ANNUAL AVERAGE OF EVOLUTION OF DIFFUSE RADIATION INCIDENT IN THE HORIZONTAL SURFACE AND IN THE TILTED SURFACES TO 12.85° (A), 22.85° (B) E 32.85° (C) TO THE NORTH.

In annual database groupings, there is symmetry energy with respect to culmination of the plane of the meridian, while in monthly database groupings, the energy levels and/or deviations are dependent on climatic variations of cloudiness, concentrations of water vapour (displacement of air masses) and aerosols (Souza et al., 2012). In the afternoon, especially in summer months, average hourly energies are smaller owing to increase of cloudiness and the accumulation of water vapour during the day (Escobedo et al., 2009; Furlan et al., 2012; Teramoto & Escobedo, 2012).

Fig. 4 presents the average hourly diffuse radiation incident on three angles of inclination evaluated and on horizontal surfaces. In this case, the monthly average levels of $[H^h_{D\beta}]$ were based on mean values obtained between April 1998 and December 2007. The diurnal evolution is dependent of photoperiod (to Botucatu, it varies 10.6 at 13.4 hours for the winter and summer solstices) and the limitations of the photoperiod for inclined surfaces (Iqbal, 1983). According to Burlon et al. (1991) the application of angles in different faces of exposure allows the lack of symmetry in the diurnal evolution of solar radiation when compared to horizontal.

Energetically this behavior corroborates with the literature regarding the evolution of the diurnal evolution of the components of shortwave radiation. Pai and Escobedo (2006) found that at the morning and nightfall, the values of diffuse radiation were very small and nearly equal with quantitative differentiation only during the hours around solar culmination. Between 9 and 15 hours, the diffuse radiation showed the highest values with dependence of isotropy and anisotropy radiation. The monthly average diurnal evolution showed maximum values of diffuse radiation ranging from 0.69 to 1.38, 0.59 to 1.49, 0.80 to 1.20 and 0.58 to 1.03 MJ m^{-2} h^{-1} for horizontal, 12.85°, 22.85° and 32.85°, respectively. It was observed that the tilt angles influence maximum hourly energy of $[H^h_{DH}]$ and $[H^h_{D\beta}]$ especially in the December to March (horizontal), August to November (12.85°), May to June (22.85°) and April (32.85°).

The highest hourly diffuse energy was observed in the summer due to the increase in the ratio of cloudiness (Fig. 4). In January, the highest hourly diffuse radiation levels for horizontal surface has occurred, whereas for tilted surfaces, the maximum energy values occurred during the zenithal solar passage and they were 1.33, 1.15 and 1.03 MJ m^{-2} h^{-1} to 12.85, 22.85 and 32.85° respectively. When compared to the average values of $[H^h_{DH}]$ obtained between 1998 and 2007, there were losses of 4.36, 15.77 and 11.26%, while, compared to average values obtained from concurrent measurements in horizontal surface, the gains were even greater (8.9; 18.0 and 34.8%, to 12.85, 22.85 and 32.85°). In December (Summer Solstice), the differences of diffuse radiation (noon) between horizontal and tilted surfaces ($[H^h_{DH}]$ and $[H^h_{D\beta}]$) were equal to 1.36, 1.31, 1.07 and 0.99 MJ m^{-2} h^{-1} (12.85, 22.85 and 32.85°). In winter, the highest hourly diffuse energy occurred in $[H^h_{D\beta}]$ slope is equal to the local latitude (22.85°), with averages above 0.21, 0.35 and 0.28 MJ m^{-2} h^{-1} when compared to the horizontal values, 12.85° and 32.85° (Fig. 4).

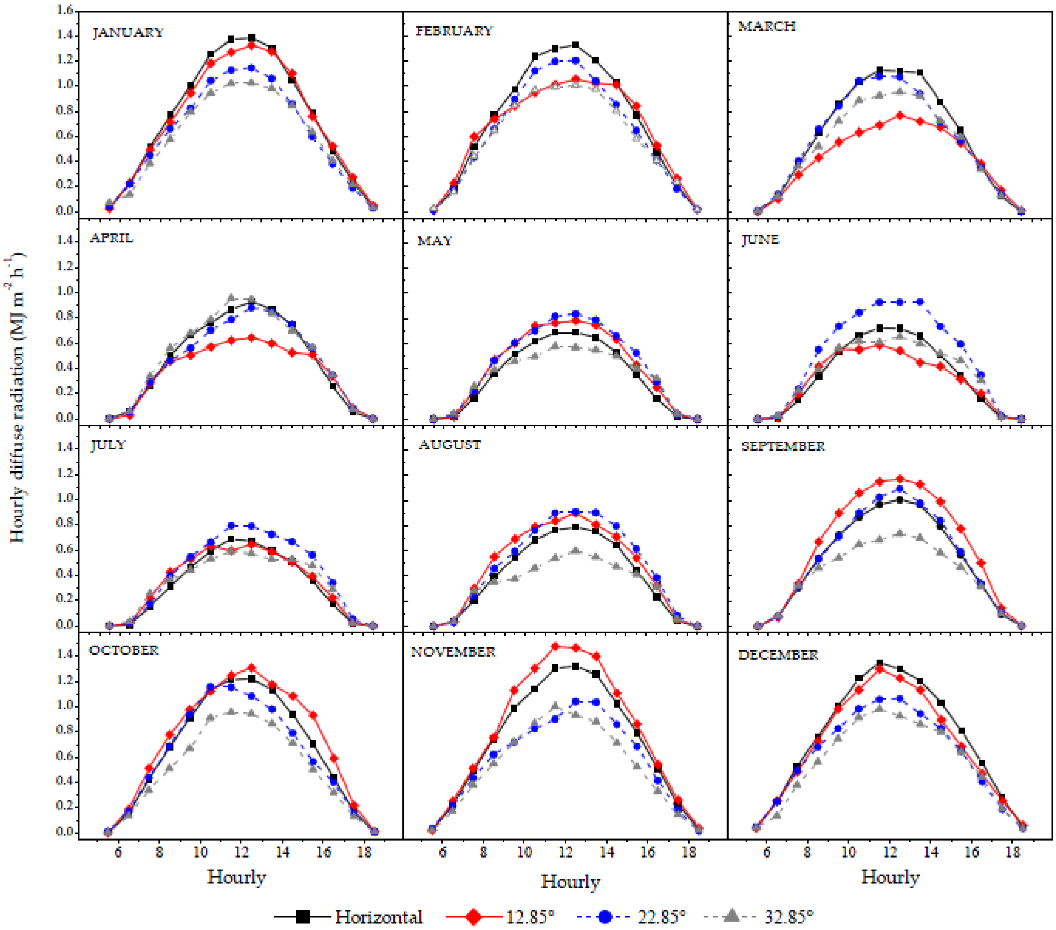

FIG. 4 MONTHLY AVERAGE OF DIURNAL EVOLUTION OF DIFFUSE RADIATION INCIDENT IN THE HORIZONTAL SURFACE [H^h_{DH}] AND IN THE TILTED SURFACES [$H^h_{D\beta}$] TO 12.85°, 22.85° AND 32.85° TO THE NORTH.

During the year, changes in the incidence of solar radiation for a given region depend basically on variations in the apparent position of the sun in relation to local latitude and climatic conditions. The solar radiation incident on tilted plane is given by the combination of the direct, diffuse and reflected components, thus any process that mitigates the passage of radiation through the air mass influences the seasonality of atmospheric transmissivity. The clouds reduce the direct component by diffusion, reflection and absorption, mainly in the infrared wavelengths [13]. Therefore, the increase of cloudiness involves the reduction of direct radiation and the rise of diffuse radiation, with decrease fo the total incident energy (Dal Pai & Escobedo, 2006; Padovan & Del Col, 2009; Pandey & Katiyar, 2009; Souza et al., 2012).

Considering the hourly partition, only in January and December, it was noticed that the increase in the inclination angle of the surface decreases the levels of diffuse incident radiation. Souza et al. (2012) observed that the annual evaluation of daily averages was the same only in February and in summer and the highest levels of [$H^h_{D\beta}$] slopes were obtained for the same latitude. Padovan and Dal Col (2010) found that in winter days, the global irradiance measured on tilted surface at 30° to South horizontal surface due to in the contribution of the direct component, since that the diffuse radiation presented levels below 100 W m-2.

The energetic differences between winter and summer enable the contribution of different sub-components of diffuse radiation. During the rainy season (summer and spring) higher concentrations of water vapour and clouds occur, consequently the diffuse radiation are higher due to the increase of isotropy. In the winter, the increase of atmospheric transmissivity allows conditions of predominance of circunsolar and anisotropic sub-components, however, in the August and September an increase in diffuse radiation occurs by influence of suspended particles (aerosols). The ratio between the direct solar radiation and the diffuse solar radiation varies throughout the day (incidence angle of the solar rays), and also with cloudy

conditions. The cloudier the period is, the higher the proportion of diffuse light is; similarly, the smaller the proportion of direct radiation is, the lower the value of global radiation is.

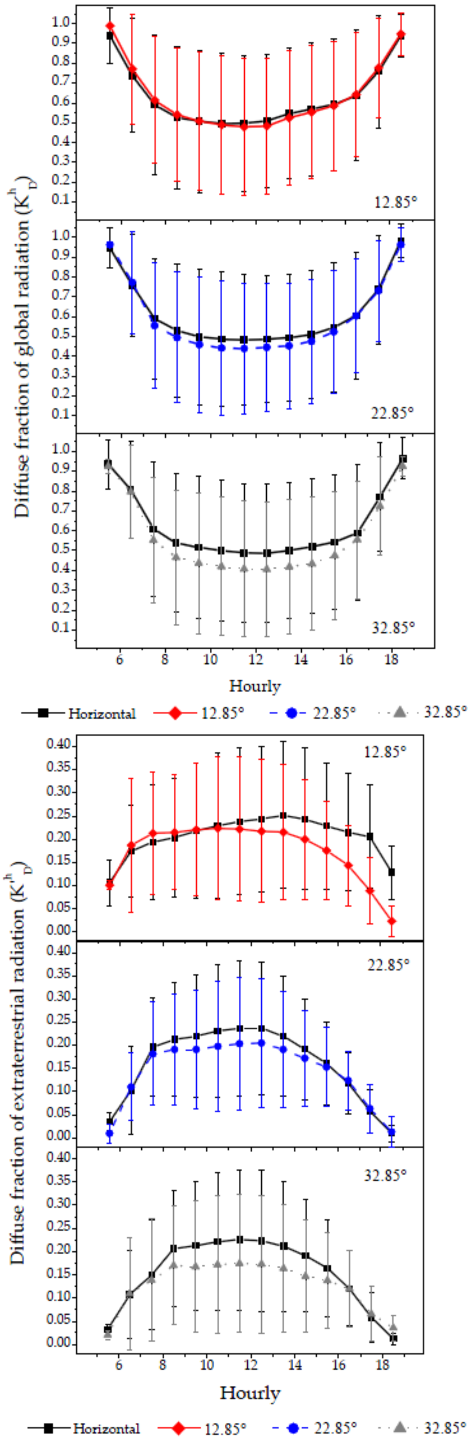

FIG. 5 ANNUAL AVERAGE OF DIURNAL EVOLUTION OF DIFFUSE FRACTION ON THE EXTRATERRESTRIAL RADIATION IN THE HORIZONTAL SURFACE [K'^h_{DH}] AND IN THE TILTED SURFACES [$K'^h_{D\beta}$] TO 12.85°, 22.85° AND 32.85° TO THE NORTH.

Between September and March, there are the largest loss of diffuse radiation relative to horizontal, whereas, the increment of the inclination angle causes the growth of losses due to the elevation of the zenithal angle (the inclined plane projection) for the same period. Considering the 12,5 hours (noon) compared to horizontal surface , reductions of 4.6, 6.5, 15.9% (September); 7.7, 12.5, and 24.8% (October); 4.5, 17.4 , 29.3% (November); 7.3, 17.6, and 31.9% (December); 8.2, 5.3, and 25.8% (January); 15.6, 11.9 and 25.8% (February); and 34.9, 9.1 and 16.9% (March) to 12.85°, 22.85° and 32.85°, have occurred, respectively. Therefore, in June , gains of diffuse radiation of 10.9% and 15.9% and losses of 8.6% for the same time and surfaces have occurred.

The annual average diurnal evolution of the radiometric fractions [K^h_{DH}] and [$K^h_{D\beta}$] showing inverse behavior when compared to evolution of annual average diffuse radiation, decrease in the passage in meridian plane due to the increase of the direct component of the incident radiation (Fig. 5).

The minimum and maximum contributions of the diffuse component in the total of global radiation were 0.48±0.34 and 0.99±0.02, 0.41±0.34 and 0.92±0.03; 0.44±0.33 and 0.96±0.01 to 12.85°, 22.85° and 32.85°. In all periods of measurements and hourly, except for moments near the sunrise and sunsets, the fractions [K^h_{DH}] were above [$K^h_{D\beta}$] and with increasing differences for higher inclinations angles.

The maximum annual average of coefficients of atmospheric transmissivity for the tilted surfaces [$K'^h_{D\beta}$] were 0.224±0.15, 0.205±0.14 and 0.174±0.15 to 12.85, 22.85 and 32.85° (Fig. 5), while for horizontal surface [K'^h_{DH}] were 0.238±0.17, 0.237±0.15 and 0.226±0.15, which were simultaneously obtained during periods of measurements on each inclination.

For these fractions atmospheric, the lack of symmetry in the annual average diurnal evolution was due to the concentration of water vapour throughout the day and consequently the anisotropy was generated in open air conditions and/or isotropy in cloud sky (Dal Pai & Escobedo, 2006; Teramoto & Escobedo, 2012). At 12.5 hours (nonn) of December (summer solstice) the minimum percentage of contribution to total diffuse component of incident radiation ([K'^h_{DH}] was obtained and [$K'^h_{D\beta}$]) of 49.37, 52.35, 41.87 and 48.79% for horizontal, 12.85, 22.85 and 32.85°, respectively (Fig. 6). Among the equinoxes, there was little variation of fractions [K^h_{DH}] and [$K^h_{D\beta}$]with averages between 8.5 and 16.5 hours, especially for smaller inclinations.

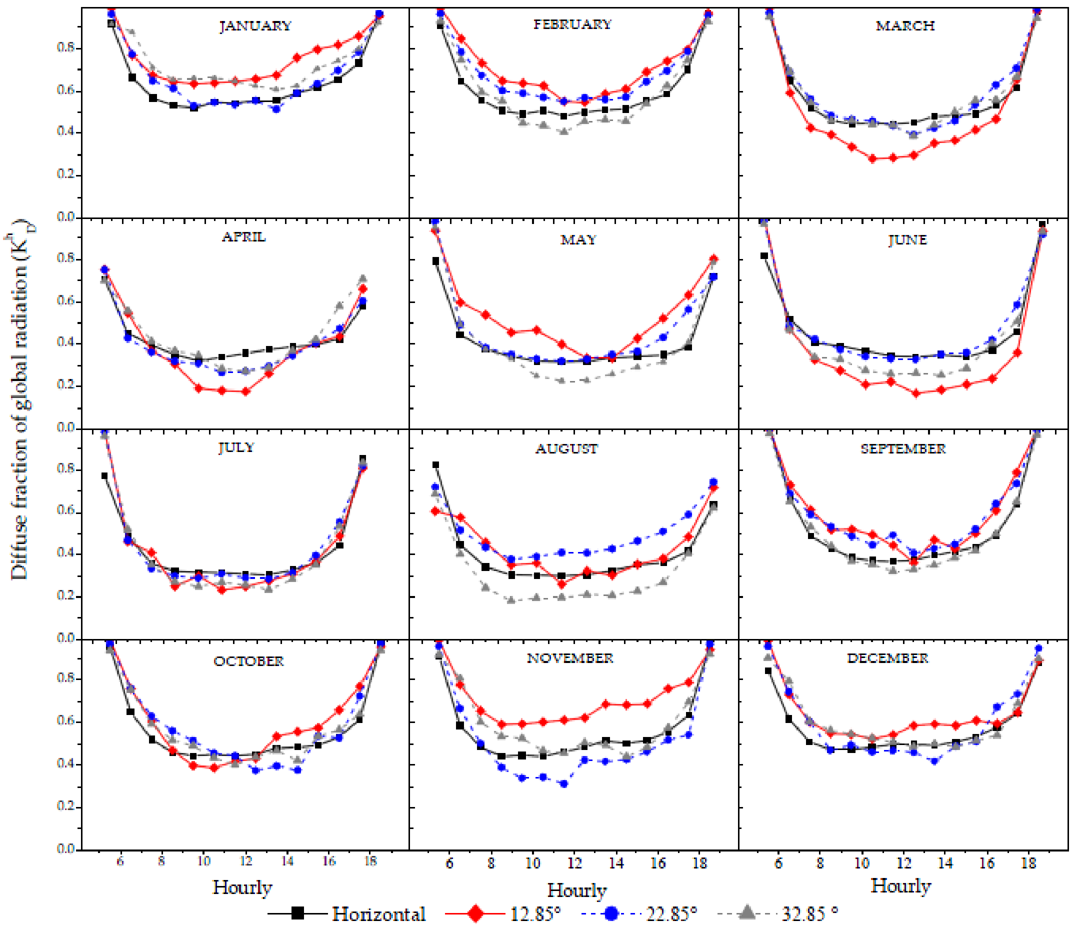

FIG. 6 MONTHLY AVERAGE OF DIURNAL EVOLUTION OF DIFFUSE FRACTION ON THE GLOBAL RADIATION IN THE HORIZONTAL SURFACE [K^h_{DH}] AND IN THE TILTED SURFACES [$K^h_{D\beta}$] TO 12.85°, 22.85° AND 32.85° TO THE NORTH.

In June, between 6.5 and 17.5 hours, the following values of [K'^h_{DH}]were found for 12.85°: 0.993, 0.473, 0.327 0.275, 0.211, 0.223, 0.167, 0.185, 0.210, 0.237, 0.360, 0.931. The relative deviations when compared to 22.85° were -1.35, 2.64, 22.85, 26.54, 38.12, 32.62, 48.82; 47 , 06, 41.68, 43.46, 38.48, and -1.64%% for the same order of times mentioned above. For 32.85° the relative deviations ranged from -2.88 (sunrise) to 36.32% (12.5 h). The values of [K'^h_{DH}] were higher than those of [$K'^h_{D\beta}$] for the lowest values of solar elevation angle.

The atmospheric transmissivity percentages increases with the inclination angle and provides higher levels of contribution to the direct radiation during winter, thus increasing the efficiency of energy conversion systems. Even with the effects of climate variability amongn years, the developments in fractions of inclined surfaces exhibit a seasonal variation. When the solar declination is positive, lower levels of the diffuse radiation occurs, whose values depend on the slope intensity of the surface with North face (the case of Southern Hemisphere). In relation to the coefficient of atmospheric transmissivity for diffuse radiation (Fig. 7) in all inclinations and months, it was noticed that near the sunrise and sunsets similar values for [K'^h_{DH}] and [$K'^h_{D\beta}$] occur, while in the other hourlies there are smaller transmissivities for inclined planes.

In winter, the inclination of 22.85° shows the highest values of [$K'^h_{D\beta}$] which have observed 0.033, 0.142, 0.206, 0.212, 0.209, 0.214, 0.212, 0.215, 0.181, 0.171, 0.130, 0.014 and 0.00 between 06.5 and 17.5 hours. By contrast, in summer, the inclination of 12.85° shows the highest values of 0.00 0.033, 0.170, 0.232, 0.233, 0.248, 0.248, 0.267, 0.250, 0.232, 0.196, 0.172, 0.150, 0.122 and 0.067 for [$K'^h_{D\beta}$] between 5.5 and 18.5 hours.

In May and August smaller fractions of diffuse radiation are observed at the top of the atmosphere, showing that, for the conditions of Botucatu, these two months have lower ratios of cloudiness, and most of the days present clear athmosphere conditions [23]. The high deviations observed in the month of June are due to the entry of cold fronts in the region to increase the concentration of water vapour.

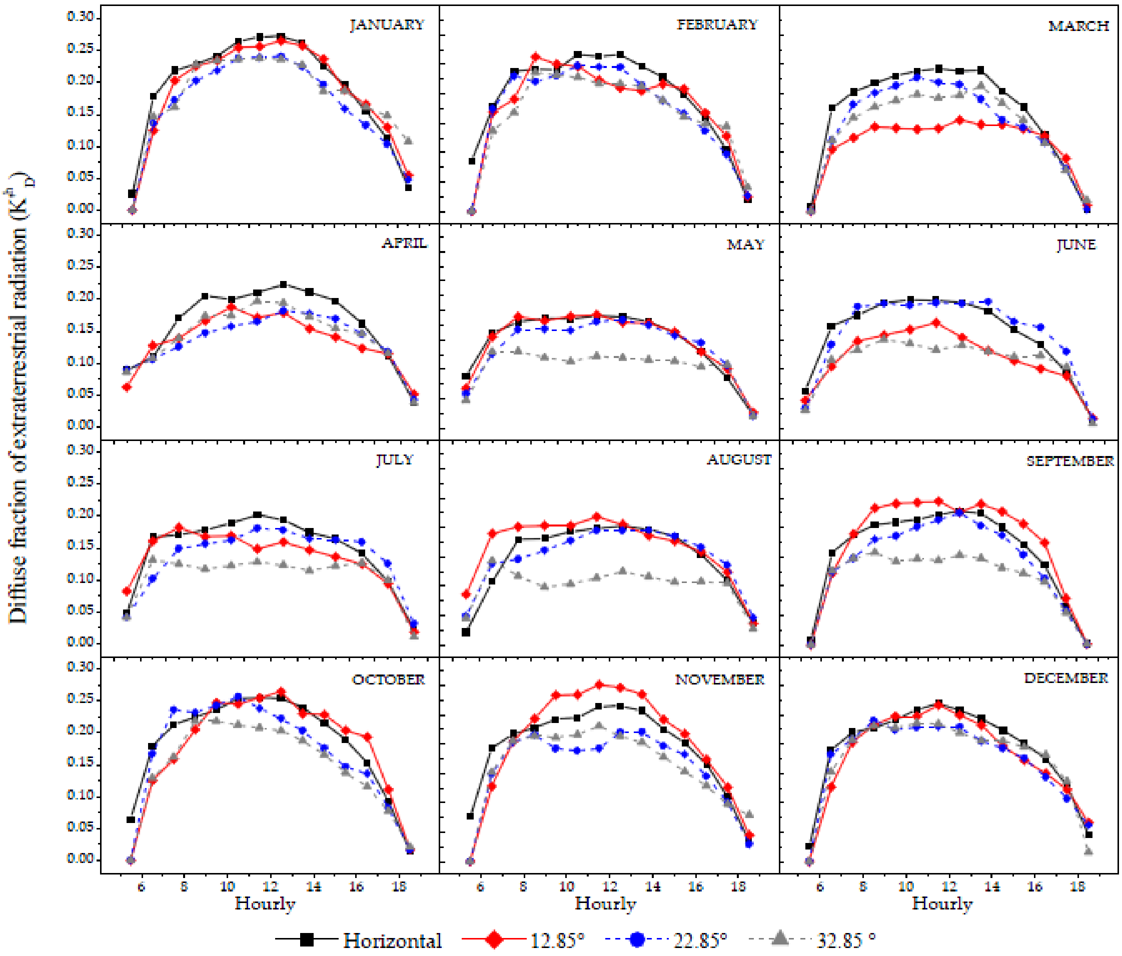

FIG. 7 MONTHLY AVERAGE OF DIURNAL EVOLUTION OF DIFFUSE FRACTION ON THE EXTRATERRESTRIAL RADIATION IN THE HORIZONTAL SURFACE [K'^h_{DH}] AND IN THE TILTED SURFACES [$K'^h_{D\beta}$] TO 12.85°, 22.85° AND 32.85° TO THE NORTH.

Conclusions

The lower diffuse energy levels occur in spring and summer by horizontal and tilted surfaces slightly facing North. The increase of the inclination angle provides greater differences energy (deviations) in tilted surfaces when compared to horizontalfor the same period of measurements due to the increase of the zenithal angle.

There is meridional assymmetry in monthly average diurnal in function of the inclination angle and climatic variations mainly related to the processes of evapotranspiration, concentration of water vapour and aerosols.

The radiometric fractions [K^h_{DH}] and [$K^h_{D\beta}$] are decreasing in the solar culmination in the plane of meridian due to an increase of component in direct radiation incident. The coefficients of diffuse atmospheric transmissivity [K'^h_{DH}] and [$K'^h_{D\beta}$] are similar to solar elevations smaller than 45°. At other hours, the tilted planes present smaller diffuse atmospheric transmissivities and with growing differences with the increment of the inclination angle.

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